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# Understanding Future Climate Impacts on Scotland's Hydropower Resource

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To encourage the development of renewable energy the Scottish Government has adopted an aggressive target of meeting 50% of electricity demand from renewable energy by 2020. As hydropower currently makes up over 10% (1383 MW) of Scotland's installed generation capacity (Department of Energy & Climate Change, 2009) it will make an important contribution towards the target. Additionally, a recent government funded study highlighted the potential for a further 657 MW of new capacity (Nick Forrest Associates Ltd., 2008), while Scottish and Southern Energy (2009) has announced its intention to construct 2 large pumped hydro storage schemes with combined capacity of around 1 GW. As such, hydropower's importance is likely to increase in the future. The potential impact of future climate on the resource is not well understood, however, with marked changes to the seasonal distribution of precipitation widely anticipated. This paper will report findings of modelling work using a distributed hydrological model covering Scotland using the output from a regional climate model. These are compared with hindcasts driven by historic meteorological data.

## INTRODUCTION

The impact of climate change upon hydropower resource is not a new subject of study however with growing concern over both energy security and the impact of a changing climate there is a growing international body of literature in this area.

Lehner et al. (2005) conducted European scale hydrological modelling using the global scale WaterGAP model and output from two climate models, the output from which was used in conjunction with a simple hydropower resource model to produce estimates of annual change to future hydropower output. These results indicate an increase in available hydropower in the North of Europe, and a decrease in the South. Bergström et al. (2001) modelled the impact of runoff in Sweden using the HBV hydrological model forced with downscaled global climate model (GCM) data. A goal of this study was the production of water resource scenarios that may impact hydropower production and dam safety and runoff was predicted to increase in the North and decrease in the South of the country. Bell et al. (2007a) have used output from a UK focussed regional climate model (RCM) to force the G2G hydrological model to allow investigation into flood risk by developing flood frequency curves.

To investigate climate change impact upon Scottish hydropower a variant of the G2G model has been applied to Scottish catchments, instead of modelling the change in peak flows emphasis has been placed upon modelling flow duration curves, to provide understanding of effects across the flow regime.

## HISTORIC METEOROLOGICAL DATA

To accurately model the temporal variation of the historic hydro resource it was necessary to develop grids of daily rainfall. Ideally, modelling would be performed using only direct rain gauge measurements, however, the network is sparse in upland areas of Scotland – see Fig 1 (a) – so it was necessary to interpolate existing UK Meteorological Office (UKMO) gauge data (UKMO, 2008a). Inverse distance weighted interpolation was used to produce daily 1 km grids of rainfall which were then weighted using the UKMO (2008b) Standard Annual Average Rainfall (SAAR) grid (Perry et al., 2005 and Tait et al., 2006). These grids were produced for the baseline period 1961 to 1995. An example of a typical daily rainfall grid is given in Fig 1 (b). A split set test procedure was performed to determine efficiency of the interpolation model wherein on each day 10% of available gauges were excluded from the interpolation and the values recorded by these gauges compared to the interpolation results. Fig 1 (c) shows a scatter of the residuals and a good model fit was observed with  $R^2$  of 0.91 achieved over a 1 year test period. Monthly 5km grids of potential evapotranspiration were calculated for the baseline period from monthly grids of weather variables made available by the UKMO (2008c) using the FAO 56 Penman Monteith method (Allen et al, 1998).

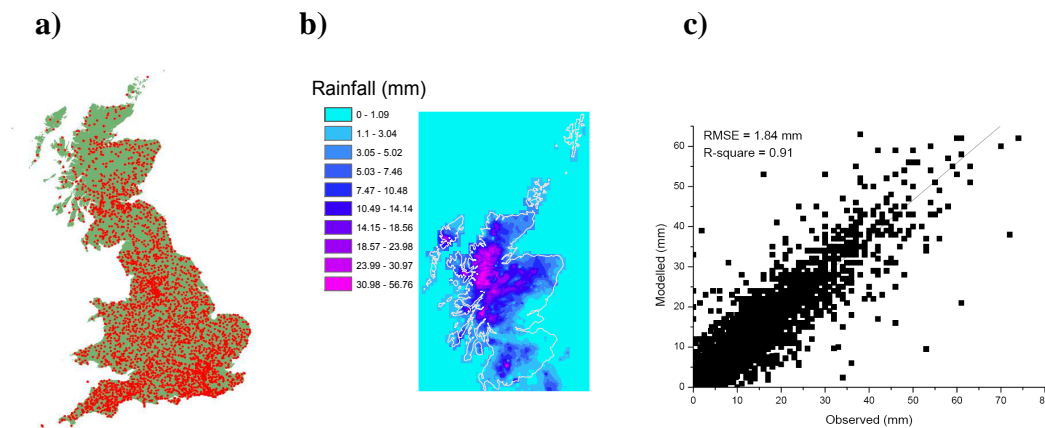


Fig 1 (a) locations of UKMO rain gauges; (b) example 1km daily rainfall grid; (c) a scatter plot of residuals for year 1982

## DELINEATION OF RIVER NETWORKS

Catchments were delineated from a 1km grid of average height derived from a 50m digital elevation model (Ordnance Survey, 2008) using Arc Hydro tools, a Geographical Information System (GIS) toolkit that enables the generation of river networks from an elevation model using the D8 algorithm (Maidment, 2002). Slope aspect is computed from elevation and classified into one of eight directions, this can be treated as a simple proxy for flow direction as it is possible to trace stream paths by moving from one grid cell to the next adjacent downstream based upon the current cell's flow direction value. The total number of cells contributing to the flow into a single cell is recorded, giving a measure of the catchment area contributing to the flow at any point in a catchment. These data form the basis of the flow routing methodology described in the next section.

The toolkit can be used to process the flow accumulation data to produce a vector hydro network using relational database techniques. Each element of the network has an associated database record detailing key characteristics and providing a representation of river connectivity. Flow time series and head data can be linked to these records providing a full hydropower geodatabase. Future work will focus upon developing algorithms to query this data to find viable hydro sites.

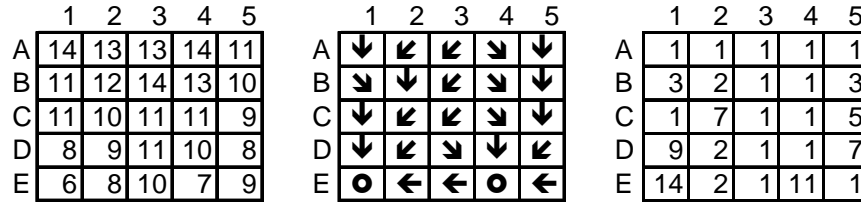


Fig 2 Creation of flow direction and accumulation grids from elevation data

## GRID BASED HYDROLOGICAL MODEL

A distributed grid based hydrological has been implemented based upon the G2G model developed by Bell *et al.* (2007 b). This model allows deterministic calculations of daily mean flow to be calculated over a wide area using a high resolution grid, in this case a 1 km grid has been used, however higher resolution grids could be used. The model is based upon a flow routing methodology utilising a 1-dimensional kinematic wave where  $q$  is flow,  $t$  is time,  $x$  is distance along the reach,  $c$  is wave speed and  $u$  is unit length of river.

$$(1) \quad \frac{\partial q}{\partial t} + c \frac{\partial q}{\partial x} = cu$$

This formula can be discretized through use of  $\theta$  to represent wave speed, and applied in two dimensions by using the value of the previous grid cell in space and time as calculated using the D8 method, where subscript  $k$  is space and  $n$  is time.

$$(2) \quad q_n^k = (1 - \theta)q_{k-1}^n + \theta(q_{n-1}^{k-1} + u_n^k)$$

Effectively a runoff weighted accumulated flow is calculated for every timestep which needed to be approximately 15 minutes to maintain numerical stability. To enable this, allow application over multiple catchments as well as future application at higher resolution, the model was coded using optimised C++.

A water balance is maintained at each grid cell, with storage increasing during times of rainfall minus surface runoff. This store is depleted by subsurface drainage and evaporation. The amount of available storage is simply based upon local gradient; therefore upland areas have less storage than flat areas. A fast surface and slow subsurface kinematic wave are simulated with return flow allowed from subsurface to surface.

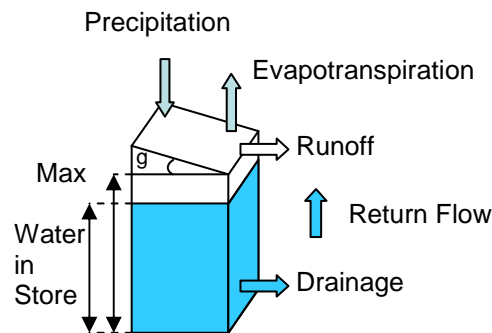


Fig 3 Water balance maintained in grid cell

## FUTURE CLIMATE DATA

The UK Climate Projections 2009 (UKCP09, 2009) project has used the output from the UKMO Hadley Centre HadRM3 regional climate model (RCM) to generate a suite of probabilistic climate scenarios. These can be used jointly with a stochastic weather generator (WG) which creates probabilistic projections of future daily weather time series to be made for 5km grid cells across the UK. The weather generator is driven by a minimum of 100 samples of probabilistic projections from the RCM producing many realisations of future climate. Therefore rather than producing a single time series of future data each WG run produces a minimum of 100 plausible time series of future daily climate.

The WG is not able to produce spatially correlated results between grid cells, however, the user has the option to select a number of grid cells producing weather time series based upon statistical properties of all grid cells in the area. UKCP09 guidance recommends against using cells with largely differing terrain in a WG run as this can produce results that are not representative of the area. This was encountered during initial trials using WG data, particularly in areas of complex terrain in the Scottish Highlands. It was found that selecting a single grid square within the catchment under study that had similar annual average rainfall to the WG baseline produced better results. This could be considered analogous to using data from a single weather station located within a catchment to force a hydrological model, which is acceptable for catchments of relatively small size. As such, only smaller catchments were considered when using the WG.

## METHODOLOGY

Using historic data the G2G model was separately calibrated for 47 gauged catchments (CEH Wallingford, 2009) over the year 1982 using the shuffled complex evolution algorithm, a genetic optimisation algorithm that can be used to find an optimum parameterisation by minimising a chosen objective function (Duan et al., 1993). As indicated by Beven (2006), initial trials using Nash Sutcliffe (Nash Sutcliffe, 1970) model efficiency as the objective function found that peak flows were overemphasised to the detriment of representation of lesser flow stages. Better results were achieved using the Heteroscedastic Maximum Likelihood Estimator (HMLE) objective function (Sorooshian and Gupta, 1995). This function assumes that model and data error will be highest at peak flows. Transforming measured and observed flows into log space using a Box-Cox transform makes it possible to reduce the skew in the data and reduce emphasis upon peak flows (Box and Cox, 1964). The quality of fit varied across catchments. Six catchments with a good model performance and geographical spread were chosen for study of climate impact: see Fig 4 and Table 1

Table. 1. Selected catchments

River	Gauge Location	Catchment Area (km <sup>2</sup> )	HMLE
Oykel	Easter Turnaig	330.7	0.78
Earn	Forteviot Bridge	782.2	0.73
Teith	Bridge of Teith	517.7	0.80
Kinnel Water	Redhall	76.1	0.80
Girvan	Robstone	245.5	0.85
Carron	New Kelso	137.8	0.81

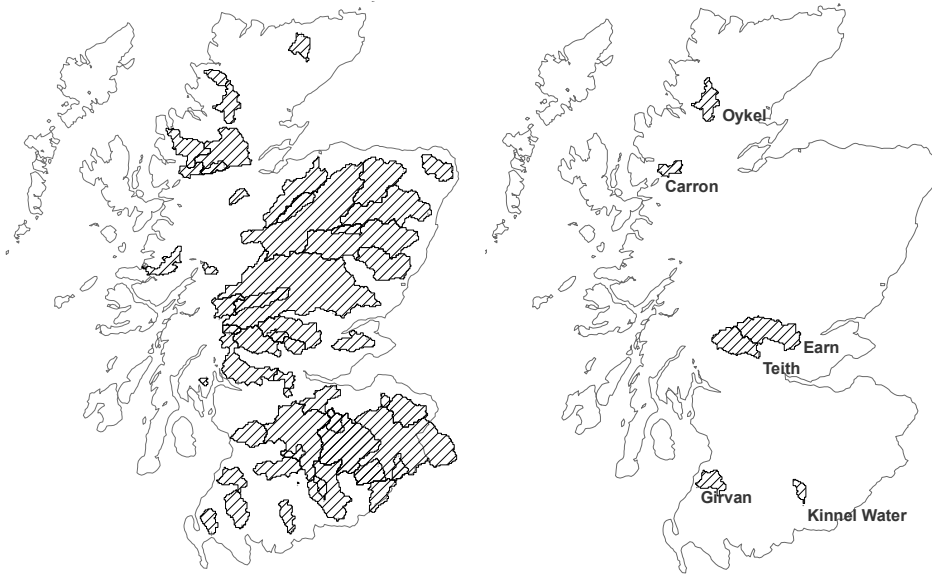


Fig. 4. Left: 47 modelled catchments, Right: 6 catchments selected for further analysis

It was found that the hydrographs produced by the model for these catchments provided a good fit to observed hydrographs. However, due to the use of the HMLE objective function and likely rain gauge error, peak flows tend to be under represented as shown in Fig 5.

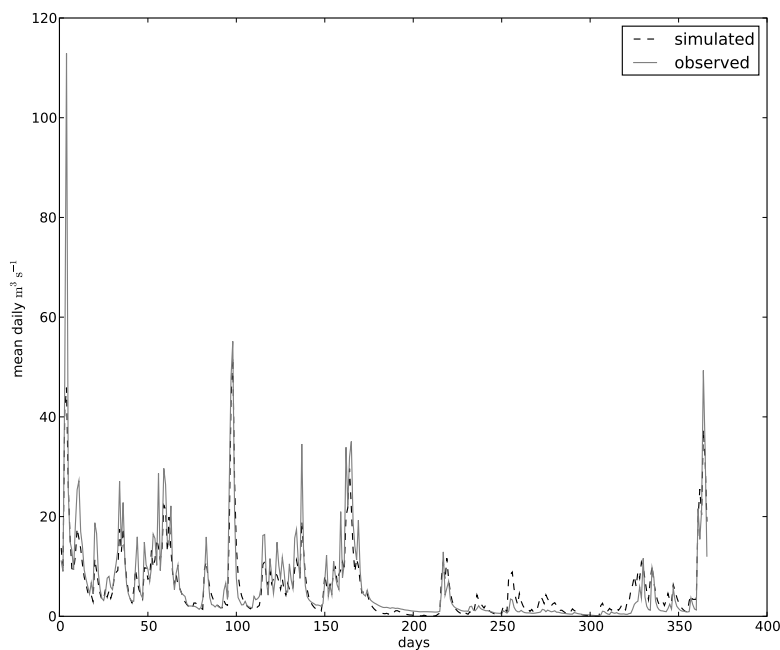


Fig. 5. Sample synthetic hydrograph

To investigate climate impact upon flow regime, the 6 selected catchments were modelled firstly using historic data to produce a hindcast flow duration curve (FDC) for the period 1961 to 1995 (the baseline period used by the WG). Modelling was then repeated with 100 sets of daily time series output from the WG for the medium emissions scenario over the period 2040-2050. Care was taken to ensure that FDCs produced by the model when forced with the WG baseline data corresponded with the hindcast FDCs and observed historic FDCs – see Fig

6 and Fig 7 left. The difference between FDCs produced from the baseline WG data and future WG data are indicative of the potential for change to the flow regime.

## RESULTS

Figure 6 and 7 show the results of the modelling for the six catchments under study. It should be noted that as each of the 100 sets of WG baseline and future data were used to force a separate simulation there, effectively 100 flow duration curves have been produced for both the baseline and future periods. To show these graphically the mean has been plotted with bars representing  $\pm 2$  standard deviations. A good fit can be seen between the hindcast produced by the model when forced with both historical meteorological data and the baseline output from the WG. Both these output compare favourably to the observed FDC from the baseline period however there is clear bias particularly above Q50. This can be attributed to systematic under measurement of extreme rainfall events and high level snow. This is likely exacerbated by the choice of HMLE as a likelihood function. Despite this clear bias the reproduction of the modelled 1961-95 FDC by the model forced with baseline data from WG increases confidence in the future climate data produced by the WG.

There is a clear increase in the rainfall across much of the flow regime during the winter (January to April), across all catchments modelled, whilst there appears to be a drop in flows during the summer. These results are for a single emissions scenario and it should be borne in mind that use of other scenarios may yield significantly different results.

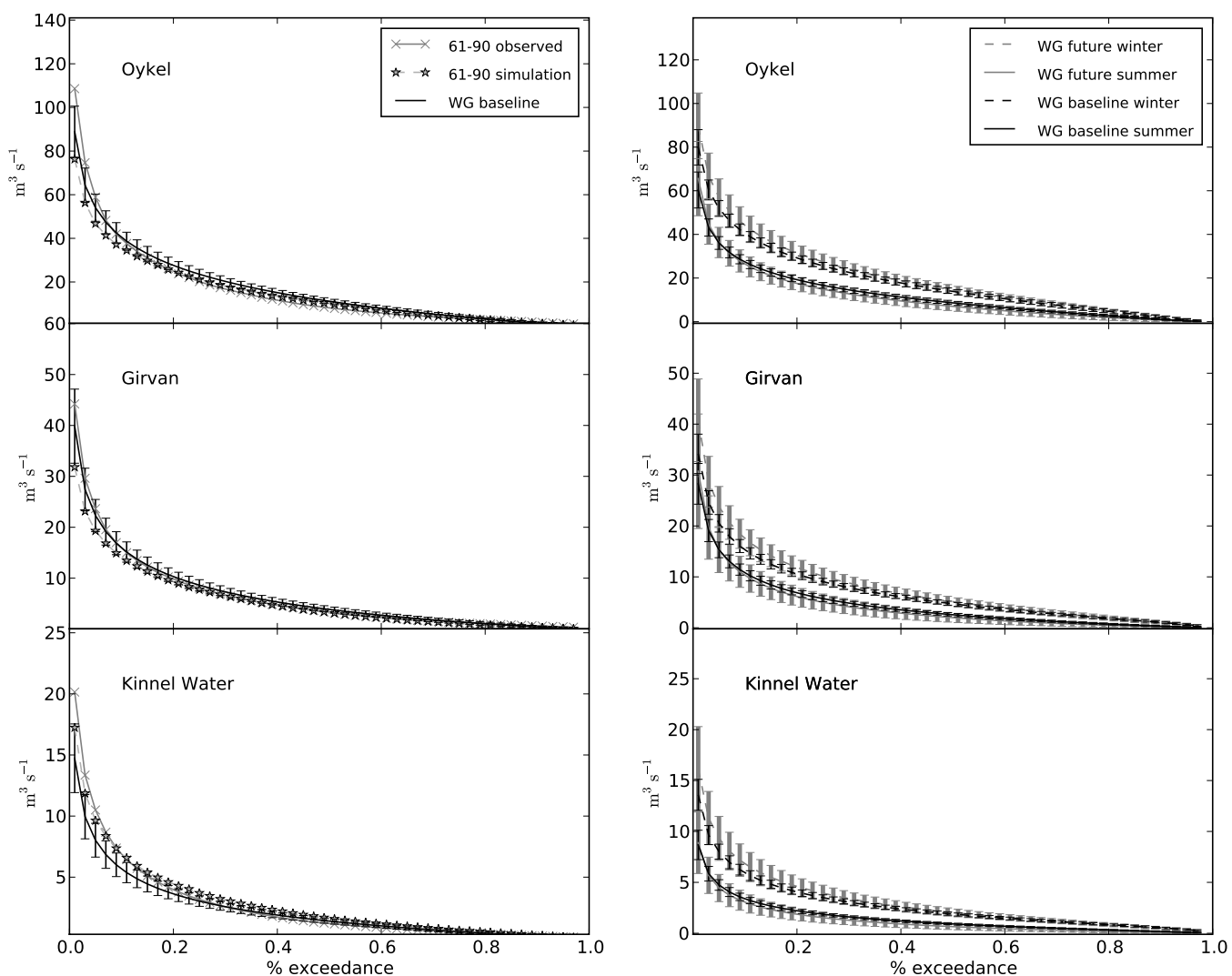


Fig.6. Left: Modelled FDCs from WG baseline runs and historic observation data compared with FDC from observed data, error bars represent  $\pm 2$  standard deviations from mean. Right: Modelled seasonal FDCs for WG baseline and WG future scenario runs error bars represent  $\pm 2$  standard deviations from mean.



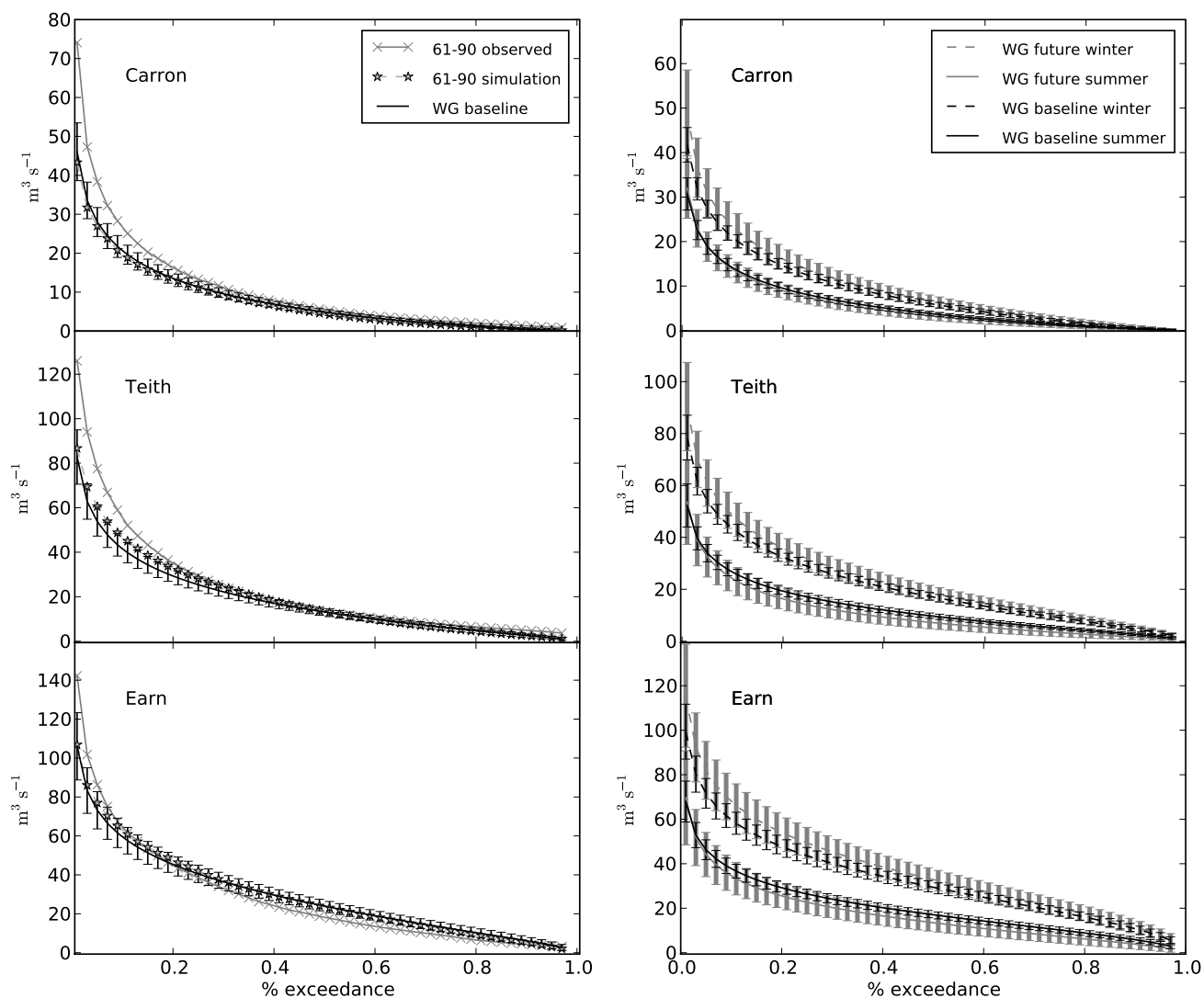


Fig.7. Left: Modelled FDCs from WG baseline runs and historic observation data compared with FDC from observed data, error bars represent  $\pm 2$  standard deviations from mean. Right: Modelled seasonal FDCs for WG baseline and WG future scenario runs error bars represent  $\pm 2$  standard deviations from mean

## CONCLUSIONS

These results compare well with those from other modelling studies in the literature. The direction of change is clear; however, the magnitude will likely vary significantly under different emissions scenarios. It is difficult to model the whole of the flow regime well using currently available hydrological models and data, leading to compromises when choosing a likelihood measure to use as an objective function. In this case an objective function has been chosen that allows a better representation of lower stages of the flow regime at the expense of peak flows. However, the greatest changes have been shown to occur at these higher stages of the flow regime.

Increased peak winter flows raise questions about the return period of severe flood events and the suitability of current spillway and weir designs. Impoundment schemes may benefit if it is possible to increase reservoir size or increase turbine capacity and are not in load or transmission constrained areas. Increases in typical mean flow may reduce overall turbine efficiency as these will have been selected and sized based upon a specific design flow.

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